Sapphire planar waveguides fabricated by H^+ ion beam implantation

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Abstract: 1.1-MeV proton-implanted sapphire waveguides are investigated for the first time. Optical measurements show that the planar waveguides support low-order transverse-mode propagation with good guiding properties without the need to anneal the samples.

OCIS codes: (230.7390) Waveguides, planar; (130.3130) Integrated optics materials

1. Introduction

The purpose of this work is to investigate the feasibility of fabricating planar waveguides by proton implantation in sapphire (α-Al_2O_3). Different types of ions were previously implanted in sapphire in order to produce optical waveguides, see [1,2] and Refs. therein. In contrast to heavy ions which modify the optical properties of the surface and produce a surface layer with higher refractive index, lighter ions such as H^+ and He^+ produce a buried damage layer caused by nuclear collision at the end of the ion tracks [1,3]. In the case of crystals, a low-refractive-index barrier is formed and the area between the barrier and the surface acts as a waveguide. He^+ implanted sapphire was previously reported, however it did not possess sufficient quality to produce good guiding properties [4]. To our knowledge, H^+ implantation has as yet not been reported for waveguide applications.

2. Experimental

The sapphire crystals used in this study were purchased from Roditi in the form of (0001) basal plane substrates with optically polished surfaces. H^+ irradiation was performed with a Van de Graff accelerator using low beam currents in the range 0.6-0.8 $\mu A/cm^2$. During the implantation the sample temperature was maintained around 30°C and the sample surface was tilted slightly off axis to avoid channeling effects. The H^+ energy was 1.1 MeV with fluences of $2x10^{16}$, $4x10^{16}$, $6x10^{16}$ and $8x10^{16}$ H^+/cm^2.

We used the SRIM-2000.40 package, a computer program that simulates the implantation process with a Monte-Carlo method, to determine the distribution of implanted ions in the sapphire crystal and the damage caused by an irradiation with H^+ of 1.1 MeV. The calculated results should be considered as a qualitative guideline only, because possible recombination processes as well as the influence of the increasing lattice disorder during the irradiation process are not included in this computer code.

The guiding properties of the ion-implanted planar waveguides were investigated using the dark m-lines technique by focusing a laser beam (λ = 632.8 nm) onto the sample through a coupling prism. The measurement of the angles of incidence which lead to light coupling into the sample allow to determine the effective indices of the modes [5]. The refractive-index profile is further reconstructed using the inverse WKB method [6].

3. Results

Optical absorption measurements performed before and after irradiation revealed the creation of color centers produced by electronic excitation during implantation. The two broad absorption bands centered around 204 nm (6.09 eV) and 259 nm (4.79 eV) can be assigned to the presence of F^+ and F centers, respectively [7]. Usually, an annealing process can remove these defects and improve the optical quality of the guiding region.

The guiding properties of the implanted samples were investigated qualitatively by end-coupling a fundamental-mode laser beam into the guiding plane and recollimating the beam out-coupled from the rear end by employing microscope objectives. Surprisingly, our implanted samples did not need to be annealed to exhibit good planar-waveguide properties. The field pattern of the waveguide modes recorded with a CCD camera clearly showed a good confinement of the excited modes in the guiding region for all four different implantation doses. As an

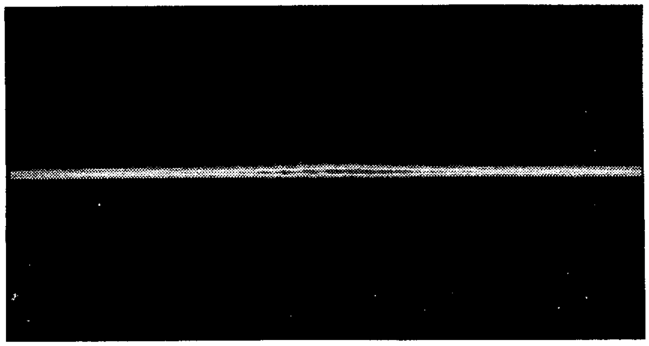

Fig. 1. Optical output profile of end-coupled, fundamental-mode laser light at λ = 785 nm from the guiding region of sapphire implanted by $8x10^{16}$ H^+/cm^2 with 1.1 MeV

illustration, Fig. 1 presents the image of the out-coupled light of a laser beam (λ = 785 nm) launched into a 1-cm long implanted waveguide (fluence: $8x10^{16}$ H^+/cm^2).

Dark m-lines measurements demonstrated that the four doses investigated lead to low-transverse-mode waveguides of good quality. This is confirmed by the thinness of the dark lines observed for both, TM and TE modes. Figure 2 shows, as an example, the reconstructed refractive-index profile of the TM modes in H^+ implanted sapphire (fluence: $8x10^{16}$ H^+/cm^2). The c-axis of the crystal is perpendicular to the irradiated surface, thus propagation is perpendicular to the c-axis (n_e excitation). In this sample, 6 propagating modes were observed. The barrier region is located at approximately 9 μm depth and is characterized by a decrease in refractive index equal to Δn = 1.3%. The depth of the barrier is in reasonable agreement with the ion-range and damage-peak distributions computed from the ion-implantation simulation code. The H^+ range calculated by the SRIM code was 10.2 μm (cf. Fig. 3) and the observed difference is within the error of theoretical range predictions usually observed for high energies.

A computation of the propagating modes of the implanted sample was performed using the FimmWave code which is a vectorial mode solver distributed by PhotonDesign. The experimental index profile was approximated to define the 2D shape of the waveguide. Simulation of the propagation led to 6 guided modes, thus confirming the experimental results.

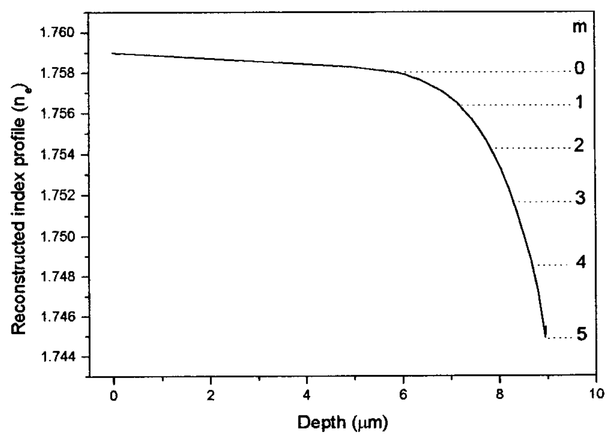

Fig. 2. Waveguide refractive-index profile for $8x10^{16}$ H^+/cm^2 with 1.1 MeV, reconstructed from a dark m-lines measurement. The dark m-lines corresponding to the 6 guided modes are indicated at the right-hand side

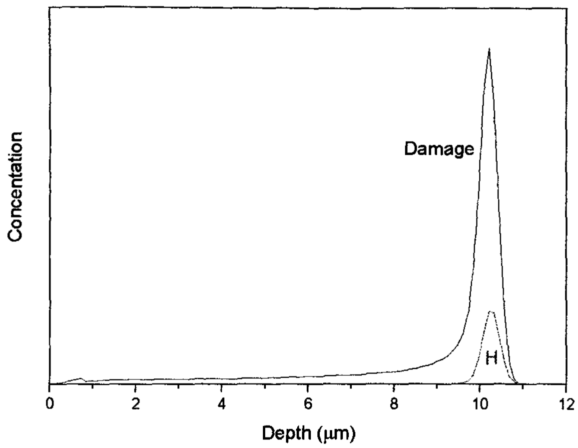

Fig. 3. Simulation of the distribution of implanted 1.1-MeV H^+ ions and damage caused by the H^+ implantation

In combination with the technologies of reactive ion etching [8] or Ar^+ milling [9], which were recently demonstrated for sapphire surface structuring, sapphire rib-channel waveguides can be fabricated. We chose a different method here to demonstrate channel waveguiding. We created refractive-index changes by spin-coating a polyimide with similar refractive index onto a sapphire planar waveguide. The polyimide was then structured by laser ablation. Optical investigation prooved channel-waveguide formation underneath the polyimide stripes.

4. Conclusions

Proton-implanted sapphire was investigated for the first time for optical waveguide applications. The results are very promising, since good guiding properties have been obtained even without annealing of the sample. The waveguides implanted so far are multi-mode, but adjustment of the H^+ energy and, therefore, the implantation depth will allow for the fabrication of fundamental-mode waveguides. Multi-energy implantation may increase the width of the damaged barrier and lead to an even better confinement of the propagating modes. Channel waveguiding was achieved by polyimide strip-loading. Possible applications of passive sapphire waveguides include interferometry (Mach-Zehnder set-up) and high-power applications that exploit the superior thermo-mechanical and thermo-optical properties of sapphire. One can also transfer the present results to Ti^{3+}-doped sapphire crystals to obtain active waveguides and possibly channel-waveguide lasers.

5. References

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